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Behind closed windows – an actor-centred analysis of barriers for the diffusion of energy efficient ventilation systems in residential buildings

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Abstract

Reaching the climate goals for the building sector requires to improve insulation and to increase air tightness of buildings in order to minimize heat loss. To achieve these goals and to prevent risks to the health of occupants and damages to the building fabric due to insufficient removal of pollutants and humidity, broad implementation of Mechanical Ventilation and Heat Recovery (MVHR) systems is crucial. Comparable and up to date figures on the market penetration of MVHR systems across the EU are hardly available. However, figures point to only a small share of residential buildings being currently equipped with such systems (cf. Riviere et al. 2009). For the German building stock the figure is estimated to be below 5 % (Händel 2011). The paper presents insights into the reasons for the slow diffusion of HRV technologies in the German building stock. It builds on the results of a recently completed research project[1] whose central aim was to identify actor-specific and structural barriers for the diffusion of efficient ventilation systems in apartment buildings and to examine how these barriers can be addressed. The analysis is based on 40 semi-structured expert interviews with energy consultants, HVAC craftsmen, and housing companies, as well as guided in-depth interviews with private owners of apartment buildings or apartments that were evaluated by means of qualitative content analysis. Based on the collected data, seven barrier categories were identified, each containing a range of single barriers for the diffusion of efficient ventilation systems within the residential building stock. Results of the analysis were quantitatively validated by means of online surveys and a household survey among 1,008 households. The paper points out interdependencies within the chain of effects leading up to the investment decision of building owners. Furthermore, based on good practice examples identified within the data collection process, it proposes different measures to address these barriers.

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Introduction

Building energy demand is an on-going concern of German climate policy. Overall, the building sector in Germany is responsible for 30 % of national GHG emissions and 36 % of final energy demand, of which two thirds are accounted for by residential buildings (Dena 2018). To reduce energy demand pertinent building regulation has been gradually intensified with regard to allowed levels of transmission heat loss through the building envelope. Thermal insulation measures implemented to comply with these provisions such as wall or roof insulation or window exchange lead to increased airtightness of buildings. As a consequence, user-independent sufficient air exchange from a hygienic and humidity protection point of view may no longer be guaranteed without adjusted ventilation techniques. Lower air permeability increases the concentration of indoor air pollutants in buildings including radon with severe health impacts on residents (Vasilyev et al. 2015; Collignan & Powaga 2019). Sources of such indoor air pollutants include construction materials, furniture, smoking or wall painting, for instance (Müller et al. 2016). From a health perspective, it is thus essential to safeguard sufficient air exchange, either naturally or mechanically.

Furthermore, while increasing airtightness reduces overall transmission heat loss, in low-energy houses, the share of heat loss through natural ventilation increases from around 24 % to 50 % (cf. Figure 1). Through the use of heat recovery ventilation (HRV) a majority of these losses (up to 83 % in passive houses) may be prevented. Accordingly, MVHR represents an important technology to achieve the political target of an almost climate neutral building stock in 2050 (cf. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2010).

However, the professional association of mechanical ventilation systems in 2014 estimated the share of existing buildings with MVHR to be less than 5 % (Händel 2011). While according to the German Energy Agency dena (2017), MVHR systems have been installed in 15 % of buildings deep-retrofitted in 2016 and in 40 % of new buildings, against the background of a persistent low rate of deep retrofits the overall diffusion is likely to be still underwhelming.

The present paper explores the barriers for stronger diffusion of MVHR systems in the German building stock. It builds on the results of a research project funded by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development. In doing so, it first presents the methodology of the analysis and its data base. Subsequently, it presents the findings with regard to HRV diffusion barriers, which have been clustered. Lastly, results on barriers are summarized and potential approaches to address them described.

Methodology and database

To examine the barriers for MVHR diffusion in existing apartment buildings, the analysis builds on the implementation of three consecutive steps. In a first step a document and literature review was performed to investigate the field of action with regard to actor constellations, the legal framework, different technologies and existing knowledge on diffusion barriers for MVHR retrofitting. Based on the latter, a first categorisation of barriers was implemented and relevant actors identified to guide the following data collection process. These comprised on the one hand of private apartment (building) owners and decision makers in housing companies as potential investors and on the other hand of energy consultants and HVAC craftsmen as providers of advisory and installation services.

To further explore the field and to capture the different perspectives of these actors and their specific barriers, in a second step semi-structured problem-centred expert interviews with ten representatives of each group (40 in total) were conducted. The interviews focused on actor specific questions on experiences with Controlled Mechanical Ventilation (CMV) and MVHR, the respective state of knowledge, attitudes towards the technology, assessment of framework conditions as well as possible approaches to address different barriers. The interviews were subsequently transcribed and evaluated using qualitative data analysis software (MAXQDA). The analysis was guided by previously identified barriers and barrier categories, which were amended with new findings.

To validate the findings from the interviews on relevant actor specific barriers, online-based surveys as well as a representative household survey were conducted. In these participants were presented a set of closed items to collect information on their experiences and to validate findings on identified barriers and their interdependencies. Based on the results of the interviews and the standardised surveys, findings were summarised and possible solutions to address these barriers identified.

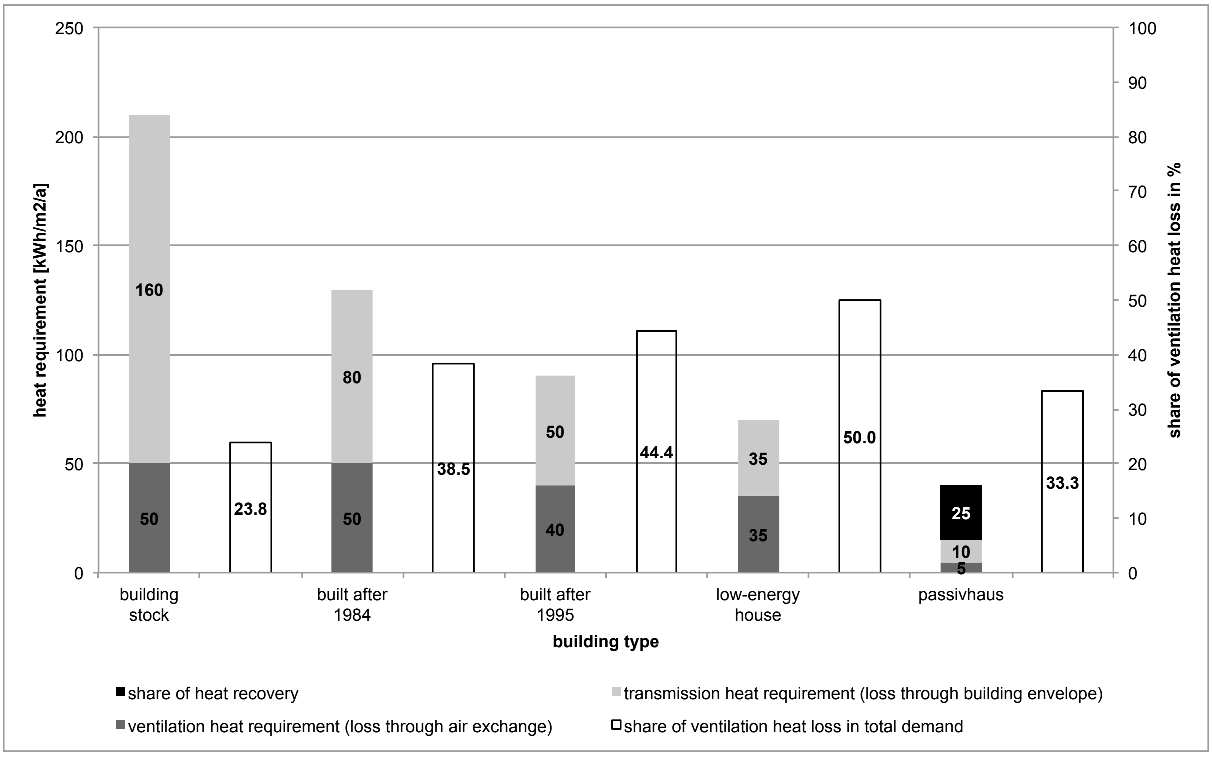

Figure 1. Share of ventilation heat loss by building standard. Source: Own Figure (based on Händel 2011).

Results

This section presents the results of interview and survey data analysis on barriers for the diffusion of MVHR. The identified individual barriers have been assigned to seven distinct barrier categories and are described with regards to their manifestation and interaction with other barriers. Some barriers are ambiguous with regards to their type and mechanism of action so that an assignment to different categories would have been arguable. An example would be fire protection regulations, which are regulatory in nature but mainly take effect via the increased costs associated with their compliance. Respective cases have been assigned with view to their primary mechanism of action.

INFORMATIONAL BARRIERS

This category comprises of barriers that relate to the knowledge and expertise, or the lack thereof respectively, of actors involved in the retrofitting of ventilation systems as well as to information access. Adequate knowledge of the relevant actors on different aspects of ventilation system retrofitting is an essential precondition for the increased diffusion of MVHR in the building stock. Energy consultants and HVAC craftsmen as designated carriers, providers and users of respective information take on a central role in this regard. At the same time, well informed owners also are more likely to invest into MVHR or to be amenable to advice from professionals to invest respectively.

Lack of problem awareness

The interviews with apartment owners showed that problem awareness for the energy losses and health risks of insufficient ventilation is often low. While owners tend to be aware of energy consumption and heat saving potentials of their real estate, there is little knowledge on the implications of air tightness increasing renovation measures for ventilation. Within energy efficiency building retrofits, investors focus on energy savings and often disregard that new windows and better roof insulation impact the hitherto natural air exchange due to pressure/temperature differences and thus mechanical ventilation measures may be required. A lack of sensitivity for the ventilation issue impedes owners to follow up on it and to look for solutions. Furthermore, it became clear that there often is no awareness for the share of heat loss through inadequate ventilation patterns in refurbished buildings.

Information deficits

Information deficits regarding building ventilation and CMV were identified as an issue within all actor groups. These related to different aspects of CMV, which in different ways may impede MVHR diffusion. Firstly, information deficits among professionals regarding **technical aspects** may result in inadequate consultation of potential investors as well as poor planning, implementation and adjustment leading to problems in the use phase (such as draughts or noise emissions). Secondly, insufficient knowledge of **legal provisions** governing the field of building ventilation has been identified as potential barrier. In light of a complex and dynamic legal framework, insufficiently informed energy consultants and HVAC craftsmen have indicated to avoid the topic altogether in order to avoid legal risks. Thirdly, particularly private apartment owners often lack information on **costs** for the retrofitting and use of MVHR, which are difficult to obtain as a layman and may thus prevent further investigation of the topic. Furthermore, professionals have been found to lack overview on **suitable funding programmes**, whose financial benefits may reduce owners' economic concerns about MVHR investment. Lastly, owners have been found to **lack overview of the CMV market** and the applicability as well as advantages and disadvantages of different ventilation systems. Closing this information gap is associated with transaction costs for own research or monetary costs for external advice and thus may prevent cost-conscious owners to follow-up on the topic.

Information access/inconsistency

Difficult access to reliable information on the performance and costs of different ventilation systems has been found to be problematic for private landlords and small housing companies with little capacities for information processing. Particularly the internet holds a rich body of contradictory information, which laymen may find difficult to disentangle in order to make an informed decision.

Information transfer

Besides content related information deficits, professionals may lack the necessary skills to properly communicate CMV-related information to potential investors. In this case, sceptical apartment owners are more unlikely to be convinced of the merits of CMV/MVHR retrofitting. This barrier may additionally be aggravated by a widespread tendency to distrust craftsmen with regard to their real intentions ("They want to sell me something").

PSYCHOLOGICAL/EMOTIONAL BARRIERS

Psychological/emotional barriers relate to various fears, attitudes and reservations towards ventilation systems, which affect the action rationale of the investigated actors. These may take effect in the context of information transfer from professionals to owners or within the eventual decision making to invest in a retrofitting or not. For owners, respective barriers may be the result of information deficits or a perceived uncertainty about various aspects such as costs, hygiene, or functionality of ventilation systems or requirements to adapt their own or tenants' living and ventilation patterns. Respective insecurities may as well translate into a psychological barrier. However, barriers in this category are not solely the result of information deficits but are also based on emotionally founded action routines and residential preferences.

Reservations

The interviews highlighted a range of reservations towards CMV, which impede MVHR diffusion in the building stock. They are either based on own bad experiences with CMV/MVHR or that of others, or result from information deficits regarding actual risks and benefits. Reservations exist with regard to **hygiene, acoustic emissions, aesthetics, costs and/or performance** of ventilation systems. Respective reservations may lead to scepticism towards CMV, decreasing chances of actors investing in or recommending MVHR retrofitting. Furthermore, tenants having such reservations are less likely to accept the associated costs and hassle of indoor installation, making it more difficult for landlords.

Lack of trust

In the context of CMV investment, information asymmetries regarding the fit and performance of different systems require potential investors to trust the assertions of professionals. Professionals again need to trust the accuracy of manufacturer specifications. The interviews and surveys have shown a lack of trust in both relationships, the existence of which presents a psychological barrier for MVHR diffusion.

Residential preferences, personal attitudes and fears

Reservations towards CMV are often a result of residential preferences, personal attitudes and latent fears shaping the interpretation of information. These comprise **risk aversion, low openness towards (building) technology, fear of autonomy loss, "fresh air fanaticism" and residential feelings**. Perceived uncertainties surrounding MVHR will resonate more strongly with risk averse decision makers, particularly in a professional context of housing companies. Accordingly, owners with respective personality traits require comprehensive information on MVHR and assurances or are else more likely to opt for less efficient low-tech options such as simple exhaust systems or window rebate ventilators. Low openness towards technology mainly but not only among older people represents a psychological barrier for MVHR diffusion. It is often connected with ideas of living, in which technical ventilation seems unnatural and is associated with a loss of autonomy. A term which has been brought up by various interviewees has been the self description of "fresh air fanatic", which reflects the need for constant and cold air streams to gain a feeling of sufficient air exchange. These psychological barriers might not be easily overcome via information transfer.

BEHAVIOURAL/PROCEDURAL BARRIERS

This category comprises a range of identified behavioural or procedural aspects that impede the diffusion of MVHR in a direct or indirect manner. On the one hand, there are necessary and possibly cumbersome coordination processes between actors involved in the retrofitting. On the other hand, instruction of users and their behaviour may strongly impact the performance of ventilation systems (particularly with regard to heat recovery), which indirectly shapes technology acceptance. Since behaviour reflects attitudes against the background of perceived framework conditions, there is a direct link to the above described psychological/emotional factors.

Coordination between actors/transaction costs

To avoid unwanted results within the different phases of MVHR retrofitting (planning, installation and use/maintenance) good coordination between different actors is essential. Particularly, planners and installers need to cooperate closely to avoid deficiencies in the use phase. With regard to the perspective of landlords, time expenditure for supervision of installation works, instruction of tenants how to properly use MVHR as well as for the coordination of regular maintenance by professionals may be perceived as procedural barrier, rendering MVHR retrofitting less attractive.

User behaviour

Broad acceptance of MVHR among building owners and tenants is a precondition for stronger diffusion and is largely based on perception of its added value against the background of efforts and costs for implementation and use. Whether ambient, energy related and economic benefits of MVHR will be realized, depends on skilled implementation and on adequate user behaviour. In cases, where users do **not adapt their ventilation habits** following MVHR retrofitting (i.e. restrict from additional manual ventilation in the cold season) **or properly operate and maintain ventilation systems**, outcomes are likely to be unsatisfactory, eventually leading to discontent with the technology. In light of actual or expected costs of use or perceived discomfort, tenants have been reported to sometimes **actively sabotage** CMV/ MVHR systems via the blocking of vents or the switching off of systems, which may result in mould related damages to the building substance. The anticipation of respective risks and possible conflicts with tenants may prevent landlords to invest into user sensitive technology such as MVHR.

Insufficient user instruction

Inadequate user behaviour may be the result of information deficits or reservations towards MVHR originating from insufficient user instruction on its function and potential benefits. Particularly in rental buildings with high tenant fluctuation, landlords are faced with the challenge to institutionalise an adequate technical and behavioural instruction of new tenants. Associated efforts in terms of time and/or monetary expenditure may negatively affect economic calculation of large-scale landlords and thus deter respective investments.

STRUCTURAL BARRIERS

Structural barriers comprise different sectoral framework conditions and actor constellations, which shape the diffusion of MVHR. With regard to their effect, they could in parts also be labelled a different barrier type.

Overall renovation backlog

Chances for MVHR diffusion in the building stock are closely connected with general trends of (energy efficient) building renovation due to a number of reasons. Firstly, according to German building regulations, renovation measures that increase air tightness of buildings require the development of a ventilation concept to ensure a sufficient level of air exchange. Secondly, comprehensive building renovations represent windows of opportunity to combine different measures in a holistic concept and to make use of synergies to limit indoor interventions (e.g. by integration of ventilation ducts into thermal insulation). The "hassle factor" associated with such interventions has been identified a central barrier for the adoption of low-carbon building systems (de Vries et al. 2019). Accordingly, acceptance of tenants for MVHR measures is likely to be higher if the installation is not perceived as an additional hassle but part of a holistic modernisation project. Lastly, good thermal insulation is a central precondition to ensure the energy performance of MVHR thus representing a buildings physics basis for its diffusion. Accordingly, the current overall renovation backlog also negatively affects diffusion of MVHR in the building stock.

Conditions for refinancing/User-investor-dilemma

Similar to other building energy efficiency measures, MVHR retrofitting in rental buildings is hampered by the discrepancy in cost-benefit distribution also known as **user-investor-di-**

lemma. Due to German building regulations that allow only a small fraction of retrofitting costs to be added to monthly rents at once (so called **modernization levy**), as well as limited willingness or ability of tenants to pay more for the measure, the prospect for landlords to refinance respective investments within a short timeframe or even at all is unclear. Generally, **demand** for dwellings equipped with MVHR currently is still too low to incentivise-increased investment for the retrofitting in existing buildings. Against this background, for the purpose of humidity protection landlords may opt for cheaper but less efficient options such as exhaust systems with inlet valves. Furthermore, **energy prices** remain at a level that does not incentivise owner occupiers to fully realize energy efficiency potentials. Also in times of low interest rate credits at capital markets, targeted **funding programmes** due to time-consuming application procedures, extensive verification requirements and less leeway regarding investment decisions have been found to be **little attractive** for the financing of building investments.

Situation in the craft sector

The crafts take on a central role in both the promotion of MVHR retrofitting as well as its correct installation. Currently, many HVAC crafts businesses in Germany however choose not to deal with the topic or provide respective services due to a number of reasons including complexity of the matter, a different business focus, liability risks as well as low demand/economic attractiveness. Accordingly, building owners may find it **difficult to find qualified crafts businesses** to implement MVHR retrofitting, which increases associated transaction costs.

The problem is further aggravated by **low capacities of crafts** due to a persistent construction boom and a shortage of apprentices and successors for retiring managers. Furthermore, measures that increase building air tightness are usually not implemented by HVAC professionals. Therefore, they often **lack knowledge** on the requirements for a ventilation concept or how to implement it. Moreover, there is a structural **conflict of interest** to communicate the potential necessity to invest in CMV due to the own measures implemented as this may deter customers. Lastly, it is estimated that there is a high share of **illicit work** in the German building sector (cf. Oebbeke 2017), which is implemented by moonlighters lacking qualifications and/or attention for ventilation matters.

ECONOMIC BARRIERS

Economic barriers aggregate all aspects affecting the costs and consequently the perceived economy of MVHR retrofitting. Here the perception of potential investors consisting of private apartment/apartment building owners and housing companies is at the heart of analysis. However, due to their role as carriers, interpreters and communicators of respective information also actors involved in the planning and installation process play an important part by shaping this perception. Economic barriers may be divided into monetary costs occurring within the different implementation phases (i.e. planning, procurement/installation, use) and factors affecting the cost level and/or the refinancing of MVHR investment (see also structural barriers) or its economic appeal respectively.

Overall costs/economy of MVHR

The overall costs and the (perceived) economy of MVHR retrofitting represent a central decision criterion for building owners to invest or not. These consist of different cost components whose levels are shaped by a variety of factors. Firstly, **costs for planning and installation** of MVHR in existing buildings exceed those for simple CMV solutions due to its performance requirements. MVHR systems require a certain level of air tightness to operate efficiently. In existing buildings, the achievement of respective levels may thus require thermal insulation works (including the change of apartment doors). Accordingly, the probability of MVHR investment is contingent in terms of energy demand of the building in question or an already existing intention for comprehensive energy efficiency refurbishment. Planning and installation costs further differ depending on the system type, building characteristics, applicable regulations (particularly regarding fire protection) and qualifications of the implementing actors. Secondly, **costs of HRV systems** themselves and their **components** represent a major part of overall costs and thus largely shape economic considerations of potential investors. Against the background of different reservations and other obstacles, these costs are broadly considered too high for an increased diffusion. The third cost component is **operating costs**, which result from the use and maintenance of MVHR systems. These comprise costs for auxiliary energy as well as service and component costs (e.g. filters) for system maintenance and repair. The reference points against which building owners compare costs within their economic assessment differs depending on whether they rent their property or use it themselves. Owner occupiers compare overall costs against potential heat energy cost savings but also consider other comfort related aspects as well as opportunity costs within their decision. Landlords on the other hand may pass on different cost components in parts (investment costs) or fully (use and maintenance costs) to tenants, whereby their anticipated acceptance and/or willingness/ability to pay and the derived chances of refinancing becomes the focal point of reference for investment decisions.

Availability of low cost alternatives

Ventilation related investment decisions ideally consider all available options with regard to their advantages and disadvantages. Due to reservations towards MVHR and in light of its complex and more costly implementation, low-tech solutions such as window rebate valves/ventilators (in combination with or without exhaust systems) or the removal of window gaskets are often the preferred option of building owners. While their implementation can ensure humidity protection and improve energy efficiency in comparison to manual ventilation, they may not achieve required air exchange from a hygienic point of view nor fully realize the energy saving potential.

Other investment priorities

MVHR investment decisions of housing companies and private landlords mostly occur against the background of limited financial resources and thus compete with other building investment areas/options. MVHR for many actors currently still represents a “luxury feature” which falls back behind priority measures such as the renovation of sanitary facilities, barrierfree access or other energy efficiency measures. Respective investment priorities also reflect demand and willingness to pay of tenants.

Low economic attractiveness of CMV as business field

Interviewed craftspeople pointed to the low willingness of customers to pay for upfront planning and consultation services in cases where they decided not to invest. In light of the significant efforts required to provide these services in a qualitative manner, this represents an economic risk for HVAC companies, which lowers the attractiveness of MVHR retrofitting as business field particularly for small companies. In combination with the overall complexity of matter, liability risks as well as low demand it provides an explanation for the comparatively low number of HVAC businesses specialised on MVHR retrofitting.

REGULATORY BARRIERS

The regulatory framework defines requirements for the field of CMV, which in various ways affect the diffusion of ventilation systems in the building stock. Regulatory provisions take effect only indirectly via the perception, processing and abidance by different stakeholder groups. Accordingly, with regard to their mechanism of action, regulatory barriers may in part also be considered other types of barriers. As an example, efforts for technical implementation (see technical barriers) and associated costs (see economic barriers) may change as a consequence of novel regulatory provisions. Furthermore, energy performance standards for buildings and ventilation systems may have an impact on the market by effectively making MVHR a necessity in buildings or through their impact on the performance of available ventilation systems and both their procurement (indirectly) and operating costs (directly) respectively. Building ventilation regulations may also impede the diffusion of MVHR. This may be the case if they are characterized by a high level of complexity, provide too much leeway regarding their interpretation or are thwarted by other regulation. As a consequence, actors in charge of implementing them may be overstrained, potentially leading to misinterpretation or even ignorance of provisions and eventually follow-up problems in the use phase. Accordingly, the impact of complex or ambiguous regulation is moderated by the qualification and knowledge of those actors. Adverse outcomes of regulatory barriers may be aggravated by a factual enforcement deficit (i.e. a lack of implementation control by competent state institutions).

Enforcement deficit

The effectiveness of energy efficiency and ventilation related building regulation depends on the level of compliance among targeted actors. In Germany the federal states are responsible for compliance monitoring and to define competent authorities for the task. In most cases this task has been delegated to the local building authorities. Due to a lack of personnel capacities (Brand/Steinbrecher 2016) and shifting priorities in light of increasing housing shortage in conurbations, compliance verifications are rare and often only occur on occasion. Accordingly, an estimated significant enforcement deficit (Hertle et al. 2006) decreases the risk of non-compliance and thus incentives to invest into CMV.

Fire protection/Preservation order regulation

German fire protection regulation is among the strictest globally and thus requires the compliance with extensive safety standards, particularly for CMV systems connecting different building parts. In consequence, the retrofitting of building central systems becomes significantly more expensive due to the required installation of fire dampers and other necessary measures plus maintenance, thus making it ultimately uneconomical.

Furthermore, whether wall openings required for retrofitting apartment or room based MVHR is in compliance with preservation order may present a source of insecurity for building owners. Authorisation of respective measures in listed buildings is decided by competent authorities on a case basis. Accordingly, transaction costs for obtaining authorization against the background of low predictability may present a barrier for further activity.

TECHNICAL BARRIERS

Technology properties, building characteristics (such as cubage, preservation order, asf.) and required work steps for retrofitting CMV/ MVHR represent technical barriers, which may complicate installation, increase costs or decrease technology acceptance of tenants. Other airing methods (such as "classic" manual ventilation) or ventilation technologies (such as exhaust systems in combination with a wall or window frame inlet valve) require less planning and alteration of the building envelope and thus are less affected by these barriers. From an investor's point of view, technical barriers and their implications for efforts and costs of MVHR retrofitting are of particular importance and are compared with other ventilation options.

Complexity of HRV planning

Planning of MVHR retrofitting comprises numerous calculations (e.g. of air exchange rates and for the appropriate dimensioning of air ducts and the overall system) and decisions on the selection of suitable ventilation systems and components (e.g. air ducts, sound suppressors asf.) as well as on the placement of the system and its components. Furthermore, to avoid problems in the installation phase an on-site inspection as well as exchange with other crafts involved in the installation process are recommended. Accordingly, the planning requires significant efforts and qualifications, which HVAC professionals with little capacities or experience may not be willing or able to provide.

Implementation efforts

Depending on the system, MVHR retrofitting may require comprehensive work implemented inside of dwellings. Particularly with regard to apartment based or building central systems, residents will thus experience a temporary decrease in living comfort due to restricted use of living space in which works are implemented as well as noise and dust formation resulting from potential multiple wall openings and duct and inside wall cable routing. While cabling may be avoided through use of Wireless LAN-enabled devices, the installation of air ducts may be a necessity to ensure uniform air distribution. For aesthetic reasons, the implementation of suspended ceilings to cover air ducts is common practice in Germany. Accordingly, the implementation of MVHR retrofitting usually requires the involvement of different crafts (e.g. electricians for cabling, painters for wall restoration, carpenters in cases where doors need adaptation works to ensure air tightness or air circulation), which increases required coordination efforts and costs of MVHR retrofitting. In light of this and potential conflicts with tenants, building owners may opt against MVHR investments.

Building characteristics

Implementation efforts for MVHR retrofitting may vary depending on building characteristics such as building/apartment layout, statics and location of the building. Building/Apartment layouts may complicate a post hoc placement of apartment based or building central systems and its air ducts, particularly in dwellings with low ceilings or limited indoor space. Further decrease of ceiling levels and thus space reduction via ceiling suspension may find low acceptance by residents and thus translate into a psychological barrier for HRV retrofitting. Moreover, since high ceilings are often considered an asset for prospective tenants, landlords may fear devaluation of their property on the rental market. The retrofitting of building central systems may also be prevented by building statics that do not allow internal wall openings for air duct routing. Lastly, since site-specific wind pressure affect the effectiveness of exhaust air conduction, an unfavourable location in this respect may prevent the proper performance of apartment or room based MVHR systems.

Availability of technology/Performance of HRV systems

Interview partners from both the crafts as well as housing companies criticised a discrepancy between manufacturer information and real performance, particularly with regard to noise emissions and air exchange rates. While respective issues may as well be the result of poor planning and/or installation, the opinion was widespread that the market currently does not provide adequate solutions to induce increased investment. It reflects a range of perceived issues related to performance, costs and efforts of MVHR that manufacturers need to address within future product development.

Summary and recommendations

As shown in the preceding section, there is a variety of in part interconnected and interdependent barriers impeding the diffusion of MVHR in the building stock. They take effect with the investigated groups of actors via different mechanisms of action that are based on the respective rationales of action. The relevance of these barriers must be evaluated with view to their direct and indirect effect on real estate owners' HRV retrofitting investment decision. This decision-making takes place against the background of economic, legal and technical framework conditions and is shaped by the decision maker's knowledge, problem awareness and investment priorities.

The interaction and interdependencies between actor specific and overarching barriers is presented in Figure 2. For the sake of clarity, the display is limited to the central identified mechanisms of action. Also barriers have been coloured/framed differently by type. Ambiguous cases are indicated by a split of different colours. At the end of the identified chains of effect is the (non)investment decision, which is largely (but not exclusively) shaped by three factors: founded and unfounded preconceptions, absolute and relative costs, and lack of requirement.

Reservations may be the result of bad experiences or of information deficits, whereas the former may be a result of the latter where such deficits have led to poor implementation or improper use of MVHR systems. Resulting founded or unfounded preconceptions are also shaped by personal preferences and attitudes, which moderate the interpretation of information.

Actual costs of MVHR retrofitting and use and their perception by potential investors and users respectively are another central factor. The analysis has shown that cost levels of the implementation and use of MVHR may be affected by both informational and technical factors. The assessment of these costs occurs against the background of structural refinancing conditions as well as a prioritisation vis-à-vis other investment areas. The evaluation by owner occupiers may in addition be shaped by their problem awareness. Accordingly, here again informational aspects play a role, on the one hand regarding knowledge of actual costs to be expected and on the other hand regarding health and energetic risks of insufficient air exchange.

The consideration of MVHR investment and the preceding decision to investigate the issue in the first place are largely shaped by the third factor, i.e. the lack of requirement. While housing companies consider CMV and MVHR in particular largely a "luxury feature", private owners often only on the occasion of problems deal with the technology. Due to a lack of legal and – with regard to humidity protection – technical requirement, CMV is not as present a topic for potential investors to induce further examinations and to increase demand. The currently still low demand for CMV related services impacts the perception and interest of actors involved in the consultation, planning and implementation of technical building systems to become active in the field or expand their activity respectively. This in turn would increase supply of qualified providers of CMV services.

The preceding paragraphs have shown that low MVHR equipment levels in the building stock are the result of a variety of actor specific and overarching barriers. In order to promote the diffusion of HRV an integrated concept is thus necessary that strengthens incentives for the different actors to engage in conducive behaviour. Single measures or instruments may address multiple barriers for different stakeholders. Generally, these measures should consider the identified interdependencies as well as the action rationales of the different stakeholders. The following section presents approaches and measures, which have been identified within the analysis.

IMPROVE LEVEL OF INFORMATION

As the barrier analysis has shown, there is a variety of informational diffusion barriers on different levels that promote reservations and preconceptions towards MVHR retrofitting. On the basis of this analysis a number of approaches or measures have been identified to improve the level of information among different actor groups.

Firstly, the expressed need for reliable and neutral information may be addressed via the establishment of a **web-based information platform** which provides comprehensive information and guidance for potential investors. Besides informa-

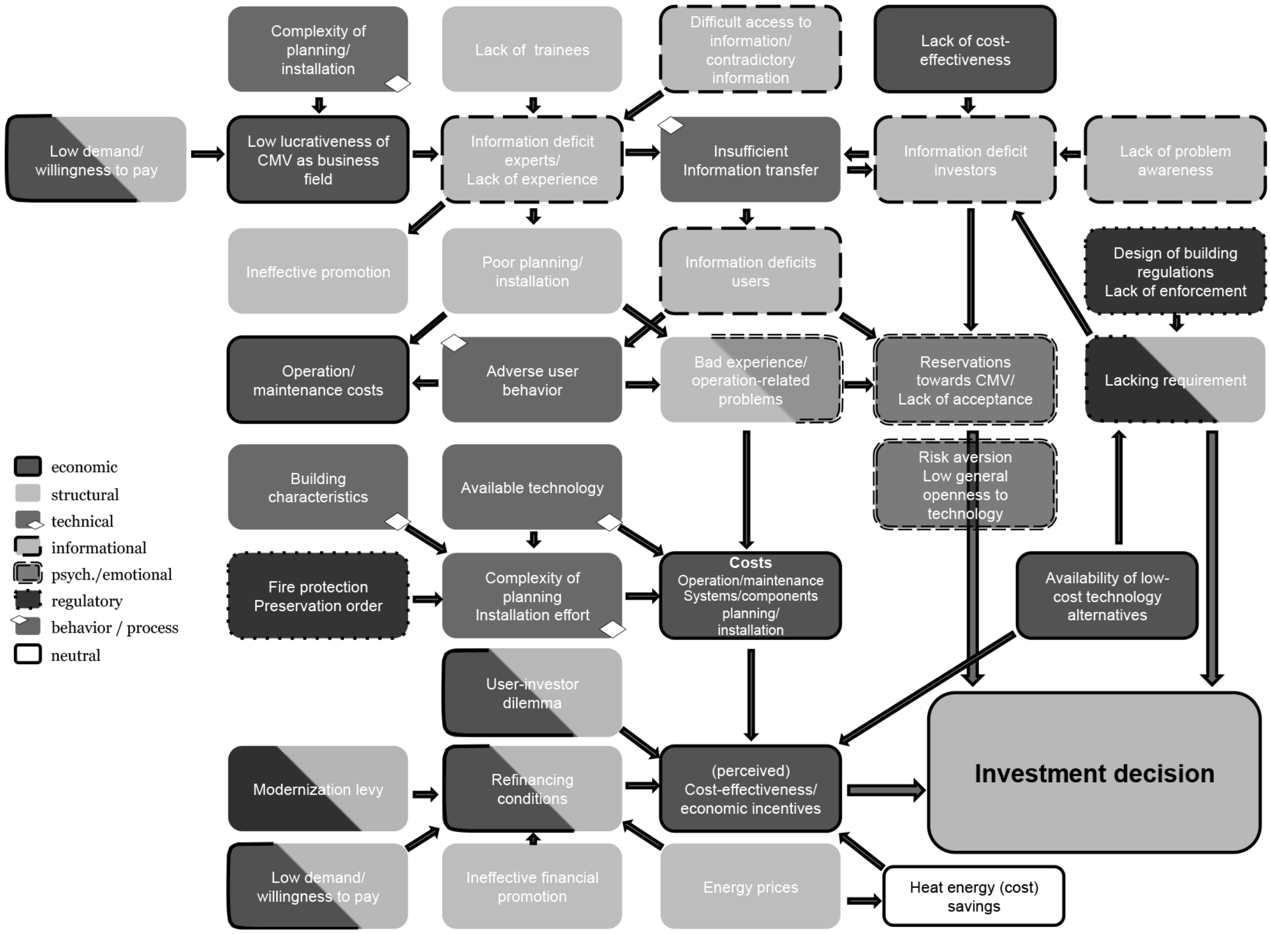

Figure 2. Overview on diffusion barriers and their interdependencies.

tion on the basic functionality of CMV/ MVHR, advantages and disadvantages of different system types, exemplary costs and funding programmes a respective platform could also provide **information on technology innovations** that may reduce implementation related barriers. The latter could provide assistance to HVAC professionals and technical directors to keep track of newest developments and thus reduce transaction costs. Secondly, in order to improve knowledge of energy advisors and HVAC craftsmen with the aim to both increase quality of advice and MVHR implementation, the **expansion of training offers and qualification requirements** may be a conducive approach. Thirdly, in order to promote information exchange between housing companies the establishment of an ***innovation network ventilation*** could provide a suitable setting, in which experiences and good practices could be shared. Lastly, the analysis has shown that professionals find it difficult to identify suitable funding programmes for their customers. To this end, a consolidation of funding programmes in combination with **facilitated guidance tools** could contribute to an improved effectiveness of support measures.

TECHNICAL IMPROVEMENTS AND INTEGRATION

Solutions to overcome technical barriers for MVHR retrofitting need to focus on the improvement of available ventilation technologies to increase their attractiveness.

The interviewed housing company executives had formulated the need for small, highly efficient, easy to maintain and **ubiquitously deployable systems** and air ducts to facilitate retrofitting. Further requests related to an improved built-in **resistance to user manipulation** in order to avoid problems in the use phase. Respective requests from the housing sector may serve manufacturers as guidance for future R&D paths. Since some of these features may come at the cost of higher prices, the market entry of innovative and highly efficient ventilation systems could be facilitated by state support programmes or bulk purchasing within public procurement for state owned residential buildings.

Innovative ideas to decrease maintenance costs or to more efficiently integrate heat recovery into the building energy flows may be leading the way. Examples comprise the installation of apartment based system devices above the front door of apartments to facilitate maintenance works and decrease associated transaction costs. Another proposal related to employing exhaust systems with central heat recovery for the preheating of not only air but also water in combination with solar thermal energy. To avoid different issues of MVHR use, the use of innovative components such as enthalpy exchangers or antibacterial air ducts may be expedient and could strengthen technology acceptance.

IMPROVE ECONOMIC INCENTIVES

Economic barriers for MVHR retrofitting may be addressed by various measures to reduce implementation costs and to improve the economic attractiveness of the technology.

The criticism of high investment and operation costs is largely directed towards manufacturers who need to adapt their portfolio to better reflect economic requirements of building/apartment owners. Another measure for manufacturers to raise attractiveness of their products may be to improve after installation support and to extend warranties thus providing more security for long-term operation. To improve economic attractiveness of MVHR retrofitting state support programmes may be temporarily scaled up to support market penetration of highly efficient systems. This could also comprise incentives for HVAC crafts to recommend and install highly efficient systems. Further efficiency improvements and thus decreased operation costs may also be achieved via stricter energy performance standards. An effective approach to disentangle the user-investor-dilemma has been demonstrated by one housing company who coupled rent increase to actual heating costs savings. Here, tenants were informed about expected heat energy cost savings beforehand and after savings had been realized, first half of them were added to the rent. In the following years rent increases were then fully matched with heat energy cost savings. This transparent proceeding has not only guaranteed technology and cost acceptance of tenants but also provided incentives for the proper use of the system. Preconditions for this approach are to ensure both the comprehensive information of tenants and proper installation.

RAISE PROBLEM AWARENESS AND INCREASE TECHNOLOGY ACCEPTANCE

Besides their contribution to reduce energy demand MVHR systems may also increase living comfort and reduce health risks related to indoor pollution. Benefits of MVHR are however largely unknown in the population; on the contrary reservations and preconceptions are widespread which are reflected in terms like "forced ventilation", which imply paternalistic technology. To help change the image of CMV, comfort and health benefits should be the focus of information campaigns. To improve outreach and credibility, the involvement of unsuspicious messengers such as statutory health insurance companies could be conducive to place the subject more prominently in the public discourse. Furthermore, the increased set up of demonstration sites, in which visitors can experience the technology first hand, may help to dismantle preconceptions about MVHR and increase technology acceptance. Moreover, sensitization for the merits and risks of proper or improper ventilation respectively may best be achieved at an early age, e.g. by integration of environmental behaviour classes into school schedules.

PROCESS OPTIMISATION AND BEHAVIOURAL ADAPTATION

A number of problems within or after implementation of MVHR retrofitting are the result of process or behaviour related causes. In the following various approaches are outlined to improve processes or behaviour related to the planning, installation and use of MVHR.

Building renovations provide windows of opportunity for MVHR retrofitting, which however may not be made use of. The application of **integral planning** as a concept for building renovations ensures that a holistic perspective on buildings is taken to avoid lock-in effects in case of partial renovations and that synergies are harnessed. In order to promote integral planning, energy consultants and planners need to be sensitized for the concept. Integral planning may be facilitated through use of suitable software which allows different crafts to include planned measures into a virtual apartment/building layout. To avoid ventilation related problems following building renovations, the establishment of **local informal networks** between different crafts may be a sensible option. Through respective exchange formats, non-HVAC crafts can be sensitized for the matter and their legal obligation to inform customers about a potential necessity for a ventilation concept. With regard to the planning and implementation of MVHR, the **four eyes principle** should be applied as standard in order to minimize risks of deficient planning or installation.

Hygiene related reservations towards CMV represents a major psychological barrier for MVHR diffusion and may result in low technology acceptance. In order to address these concerns, in addition to the three-year interval obligatory hygiene inspections, a suitable approach would be to take and examine **test samples** in air ducts and air intakes on a yearly basis.

Besides sufficient user information on the function and benefits of MVHR, a number of technical solutions have been identified to ensure appropriate user behaviour and to prevent system manipulation or switch-off of apartment based systems. Firstly, **tilting locks for windows** are low-cost options to prevent inefficient ventilation patterns. Secondly, in order to prevent tenants to turn off MVHR systems, a subtle technical option is to **restrict control** so that at zero position the system still operates to ensure humidity protection. In cases where tenants remove the fuse to stop system operation a more radical step chosen by one housing company was to attach the system to the same fuse as TV or refrigerator.

Conclusion

Moving towards zero or plus energy buildings is a necessity to minimize GHG emissions in the building sector and to achieve the climate goals of the Paris Agreement. However, a mere focus on constructing airtight buildings without adjustments in the ventilation "regime" not only increases the hazard of damages to the building (e.g. through moistness, mould), but also of losing acceptance of building owners (and tenants) for building energy efficiency regulation and the energy transition in general. MVHR-technology represents a solution for buildings to not only fully harvest energy efficiency potentials but at the same time ensure high living comfort including enhanced indoor air quality. The multitude of interconnected barriers hindering CMV-/MVHR-technology diffusion in the building stock may however not be overcome by a "silver bullet" measure. Rather, concerted action on different levels to sensitize and incentivise the different actors shaping and making MHVR investment decisions is required.

While the interviewed actor groups are at the centre of MVHR retrofit investment decisions, the analysis has identified additional stakeholders with a role to play such as property managers, architects and planners. Also, given that CMV-/MVHR-systems have been available on the German market for decades, it is unlikely that the market and particularly technology developers can pave the way for an increased uptake alone. This assumption is underlined by the finding that the diffusion of CMV-/MVHR-systems is also impeded by emotionally embedded preferences for natural ventilation. Other research disciplines may shed further light on how such psychological/emotional barriers can be overcome.

Furthermore, it can be worthwhile to extend the scope of future research to other countries with similar framework conditions to examine policies that foster CMV-/MVHR diffusion. Such a comparative perspective could also help to investigate on how other countries overcome specific barriers. Possible research questions to be examined may be: How can the lack of qualified craftsmen in the field of ventilation be overcome? How can better collaboration of different craft businesses be achieved to avoid faulty installations? And most importantly: How can public awareness for the hazards of indoor air pollution be broadly raised?

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